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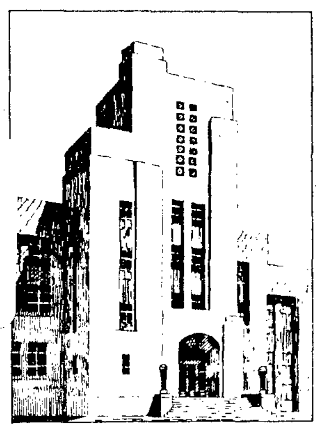
THE DAVID W. TAYLOR MODEL BASIN

WASHINGTON 7, D.C.

BOW-WAVE-DETACHMENT DISTANCE FOR SPHERES AT LOW SUPERSONIC MACH NUMBERS

by

William C. Volz



August 1954

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Symbols

b, m	constants
h	vertical asymptote
k	horizontal asymptote
M	free-stream Mach number
R	radius of sphere
x_s	axial distance from center of sphere to bow wave
γ	ratio of the specific heats
δ_s	$\frac{x_s - R}{R}$
ζ	ratio of open to total width per slotted wall
A	test section area, 70 square inches

AERODYNAMICS LABORATORY
DAVID TAYLOR MODEL BASIN
UNITED STATES NAVY
WASHINGTON, D. C.

BOW-WAVE-DETACHMENT DISTANCE FOR SPHERES AT LOW SUPERSONIC MACH NUMBERS

by

William C. Volz

SUMMARY

Tests have been performed on four different diameter spheres at free-stream Mach numbers from 1.0 to approximately 1.1 to determine the sphere bow-wave-detachment distance and to check these values with some existing theoretical and empirical methods. It was found that all of the theoretical and empirical methods investigated gave values for bow-wave-detachment distance at these low Mach numbers which were too low.

An empirical equation was obtained from the experimental data which gives satisfactory values of bow-wave-detachment distance even when the Mach number is as high as 3.0.

INTRODUCTION

One of the major problems encountered in the analysis of test data obtained from transonic wind tunnels is the effect of wall interference. At the present time considerable effort is being made to eliminate, or at least to minimize, the boundary interference. Adequate theoretical and experimental

investigations have been made which show that a problem exists only at supersonic speeds where wave reflections occur. These experimental investigations consisted primarily of comparisons between pressure-distribution data and either free-flight data or data obtained from larger tunnels.

At Mach numbers slightly higher than unity another criterion, which may be used to determine whether or not wall interference is present, is the location of the bow wave in the tunnel as compared to its location in a free stream. In order to apply this procedure, it is necessary to know the bow-wave-detachment distance of a body in a free stream.

The purpose of the present investigation is to determine the variation of bow-wave-detachment distance for a sphere in a free stream as a function of Mach number. Several methods, both theoretical and empirical, have appeared in literature. However, except for one theoretical method, these methods apply at Mach numbers greater than 1.2. The present investigation is concerned with the region from M = 1.0 to about M = 1.1. Therefore, it was necessary to determine whether or not any of the methods available would be valid in this range; and, if not, to determine a new empirical relation.

The procedure of this investigation was to test several sizes of spheres of small blockage in the 1/12-scale model of the transonic wind tunnel. This tunnel used the slotted-throat principle. The data obtained from these tests

were used as the basis of comparing the various methods available for predicting sphere bow-wave-detachment distance.

MODELS AND TEST FACILITY

The models used in this test were four spheres with diameters of 1/8 inch, 3/16 inch, 5/16 inch, and 0.404 inch. These spheres were sting supported as shown in Figure 1. The values of blockage of these models, based on percent of test section throat area, were 0.018, 0.039, 0.110, and 0.132 percent. The tests were conducted in the 1/12-scale model tunnel shown in Figures 2 and 3. The test section is 7 inches in height by 10 inches wide with slotted floor and ceiling and glass side walls. The slotted floor and ceiling were parallel; the glass side walls were divergent with an angle between the walls of 17 minutes. There were six slots in each slotted wall, each slot having a width of 0.20 inch, so that the ratio of open to total width per slotted wall, ζ, was 0.12. The slot geometry is shown in Figure 4 along with dimensions of the effusers used in this test section.

The schlieren system used to obtain the schlieren photographs is a symmetrical two-mirror system shown in Figure 5. With this system, schlieren photographs were obtained both as motion pictures and stills.

TESTS

The tests were performed at Reynolds numbers of 79,000 to 287,000 based on the diameter of the spheres. The tunnel stagnation pressure was atmospheric and the stagnation temperature varied from 126° to 161° Fahrenheit.

Each sphere was tested at Mach numbers from 1.0 to about 1.1, the maximum obtainable with the present testing equipment. At each Mach number, schlieren photographs were taken of the horizontal density gradients in the region of the model. To insure adequate data coverage two tests were performed with each sphere. The test-section Mach number was determined from the ratio of the static pressure in the tank to the stagnation pressure. The Mach numbers are accurate to ±0.005 based on a reading accuracy of the mercury manometer of ±0.02 inch. The axial variations in free-stream Mach numbers are within this accuracy. The accuracy of δ_s varies from ±0.005 for the smallest body to ±0.002 for the largest body, based on a measuring accuracy of ±0.002 inch. This is the accuracy of the actual distance obtained by measuring to 0.02 inch from a schlieren negative magnified 12.6 to 1.

The bow wave ahead of the spheres oscillated with a maximum variation in δ_s of ±5 percent at the maximum Mach number. This oscillation was measured from schlieren movies. The oscillations at the lower Mach numbers increased somewhat but the magnitude could not be accurately determined because of

inadequate movie film data.

RESULTS

The bow-wave-detachment distances, δ_s, determined for the four spheres are presented in Figure 6.

The method of least squares was applied to obtain an empirical equation representing these data. The curve was assumed to be a hyperbola of the form,

$$\delta_s = b(M-h)^m + k$$

where k and h are the horizontal and vertical asymptotes respectively, and b and m are constants determined by the method of least squares. This is the general form of the equation used in References 1 and 2, in which values used for h and k were one and minus one respectively. Data obtained from the 1/12-scale tunnel were used to calculate values of b and m using the same asymptotes. The resulting equation was,

$$\delta_s = \frac{0.767}{(M-1)^{0.596}} - 1$$

Since δ_s actually approaches zero instead of minus one as the Mach number becomes very large, the following equation, in which k was assumed equal to zero, was obtained for extrapolation purposes:

$$\delta_s = \frac{0.354}{(M-1)^{0.768}}$$

The above equations are plotted in Figure 6.

Also plotted in Figure 6 are the theoretical curves of other investigators (References 1 and 3) and an empirical equation based on the results of a third investigation (Reference 2). These three methods, which are all for spheres, are discussed below,

1. Heybey's method is given in Reference 3. The method includes higher order terms to account for entropy and flow-deflection changes across the shock. The resulting equation is

$$\delta_s = (\sigma+1)^{1/3} - 1$$

where

$$\sigma^2 - \frac{6}{5}(K-1)\sigma - \frac{9}{10}K\left[\frac{2}{\gamma+1}(K+1)^2 + \frac{2}{\gamma+1} + 1\right] = 0$$

and $$K = \frac{\left(\frac{\gamma+1}{2}\right)M^2}{M^2-1} - 1$$

2. Laitone and Pardee's method is given in Reference 1. This is a first-order approximation method in which the change in entropy and flow deflection across the shock are neglected. The resulting equation is

$$\delta_s = \frac{0.844}{(M-1)^{1/3}} - 1$$

3. Heberle, Wood, and Gooderum's method is given in Reference 2. This method consists of an empirical

equation based on data from interferometer photographs obtained at Mach numbers between 1.17 and 1.81. This equation is

$$\delta_s = \frac{4/3}{(M-1)^{1/3}} - 1$$

In Figure 7, the empirical equation with horizontal asymptote equal to zero, which was determined from the experimental data of the present investigation, is extrapolated to a Mach number of three and compared with various experimental results obtained from other investigations (References 2 and 4). The data from the Pressurized Ballistics Range were obtained directly from photographic plates on hand at the Naval Ordnance Laboratory. This ballistics range is described in Reference 5.

A typical series of schlieren photographs of the flow about the 1/8-inch sphere are shown in Figure 8.

DISCUSSION

At a given Mach number, the values of δ_s obtained in this investigation are influenced by two possible errors. The source of the first type error is the tunnel oscillations previously mentioned. The second possibility of error is a result of boundary interference existing in the model tunnel tests. If boundary interference existed, it would be expected that the interference would increase with increasing blockage. In Figure 6 at a given Mach number, there is no evidence of a consistent trend of δ_s with blockage. Therefore, the wall inter-

ference was too small to be measured within the accuracy of these tests.

It is shown in Figure 6 that all of the theoretical methods investigated give values of δ_s which are too low. At least one other investigator, Heybey, found this to be true. Of the three curves, the one based on the equation derived by Heybey has a slope variation most like the slope of the experimental points but none of the three methods gives a satisfactory indication of bow-wave detachment at these low Mach numbers.

The two empirical equations obtained from the experimental data of this investigation, given in Figure 6, show that the change in horizontal asymptote from minus one to zero does not have any appreciable effect on the shape of the curve in this Mach number range.

From curiosity, the empirical equations were extrapolated to higher Mach numbers in Figure 7. It is interesting to note that although the empirical equations derived herein were based on data over the Mach number range from 1.0 to 1.1, the extrapolated curve with horizontal asymptote equal to zero is in excellent agreement with experimental data at least out to a Mach number of 3.0. This unexpected agreement permits the determination of the bow-wave-detachment distance ahead of a sphere over the Mach number range from very near unity to a Mach number of at least 3.0 by a single, exceedingly simple equation.

CONCLUSIONS

The following conclusions can be drawn from the preceding discussion:

1. The theoretical and empirical methods checked are not accurate for supersonic Mach numbers less than 1.10.

2. The empirical equation,

$$\delta_s = \frac{0.354}{(M-1)^{0.768}}$$

which was developed from experimental data obtained at Mach numbers between 1.0 and 1.1 gives a valid indication of bow-wave-detachment distance for spheres at supersonic Mach numbers up to 3.0.

Aerodynamics Laboratory
David Taylor Model Basin
Washington, D. C.
August 1954

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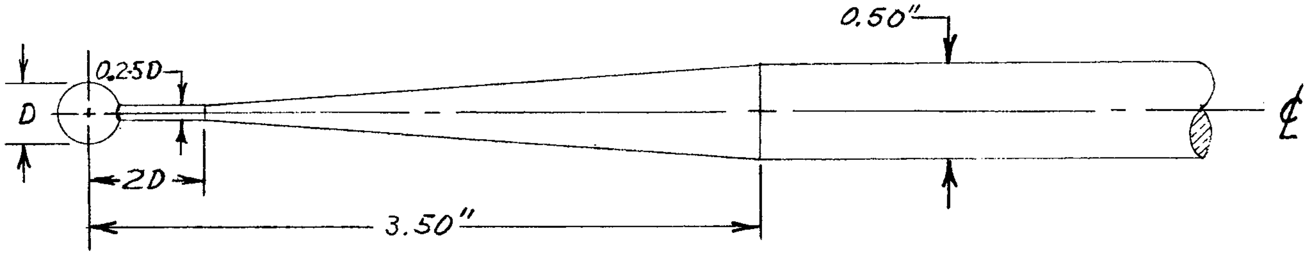

Sphere	Diameter in inches
1	1/8
2	3/16
3	5/16
4	0.404

Figure 1-Principal Dimensions of Spheres and Supports

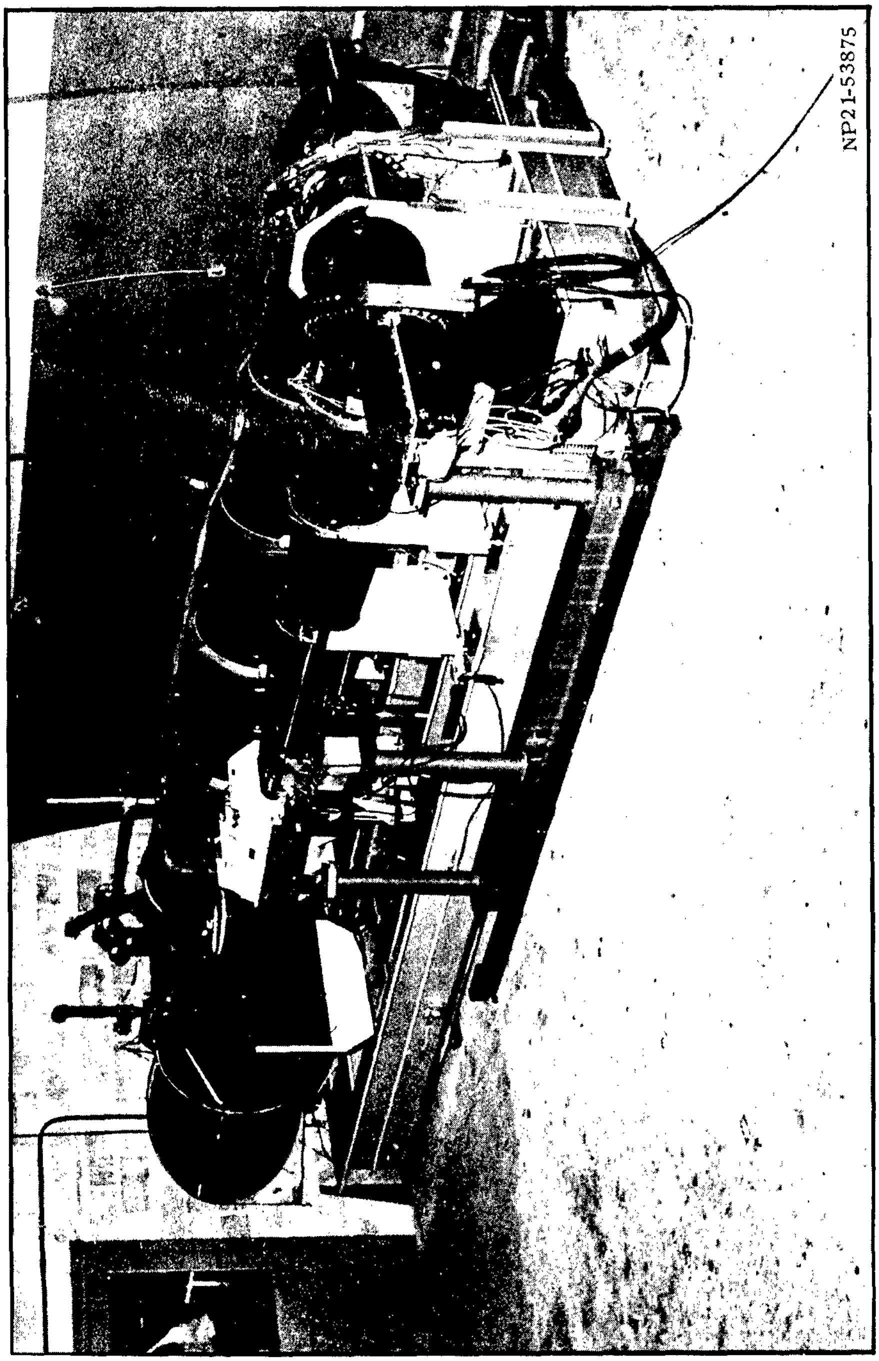

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Figure 2 - Photograph of 1/12-Scale Model Tunnel

1. Sphere
2. Sting
3. Effuser
4. Slotted Floor Panel

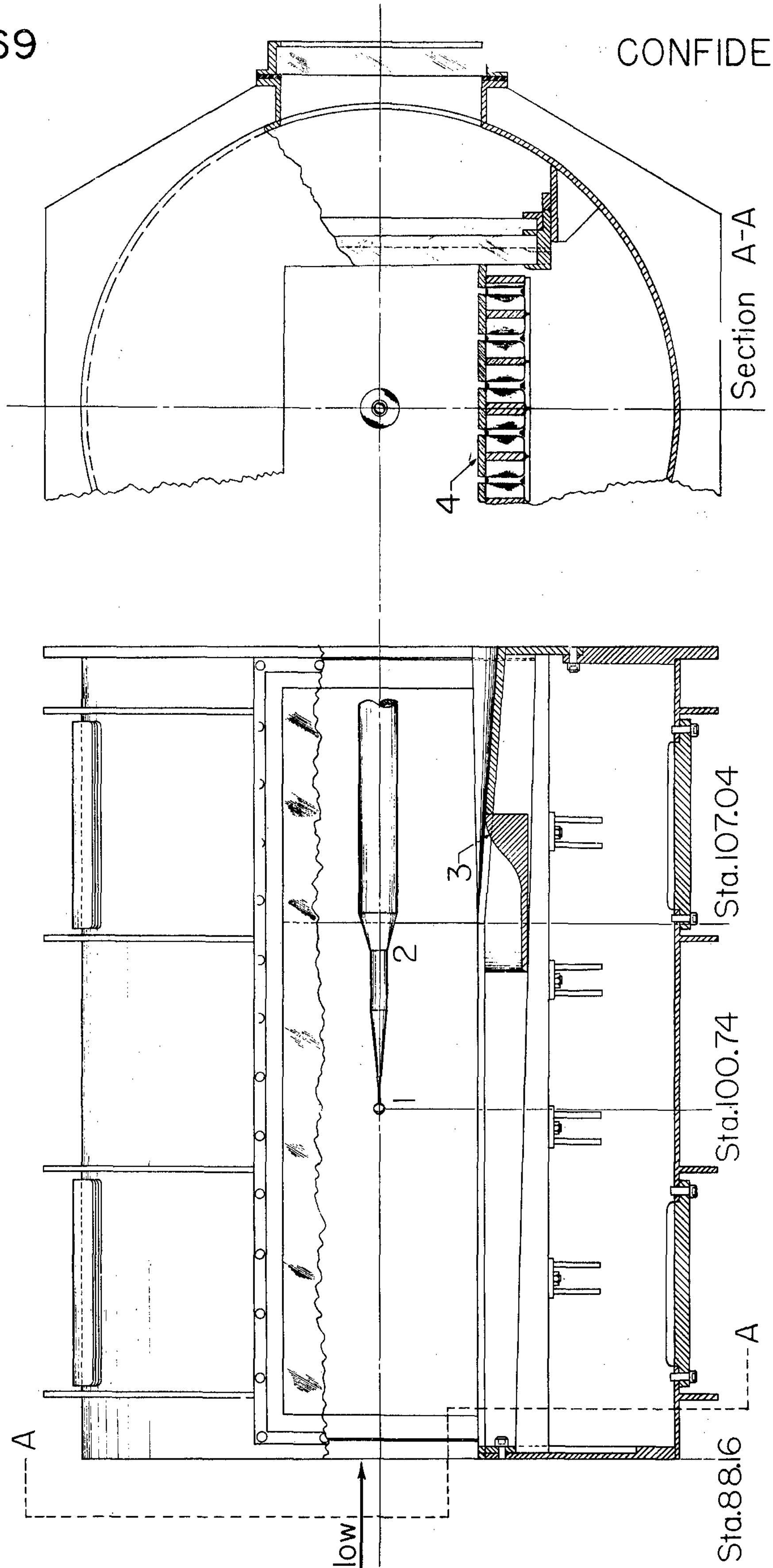


Figure 3- General Layout of 7-by-10-inch Wind-Tunnel Test Section and Plenum Chamber Showing Model Installation

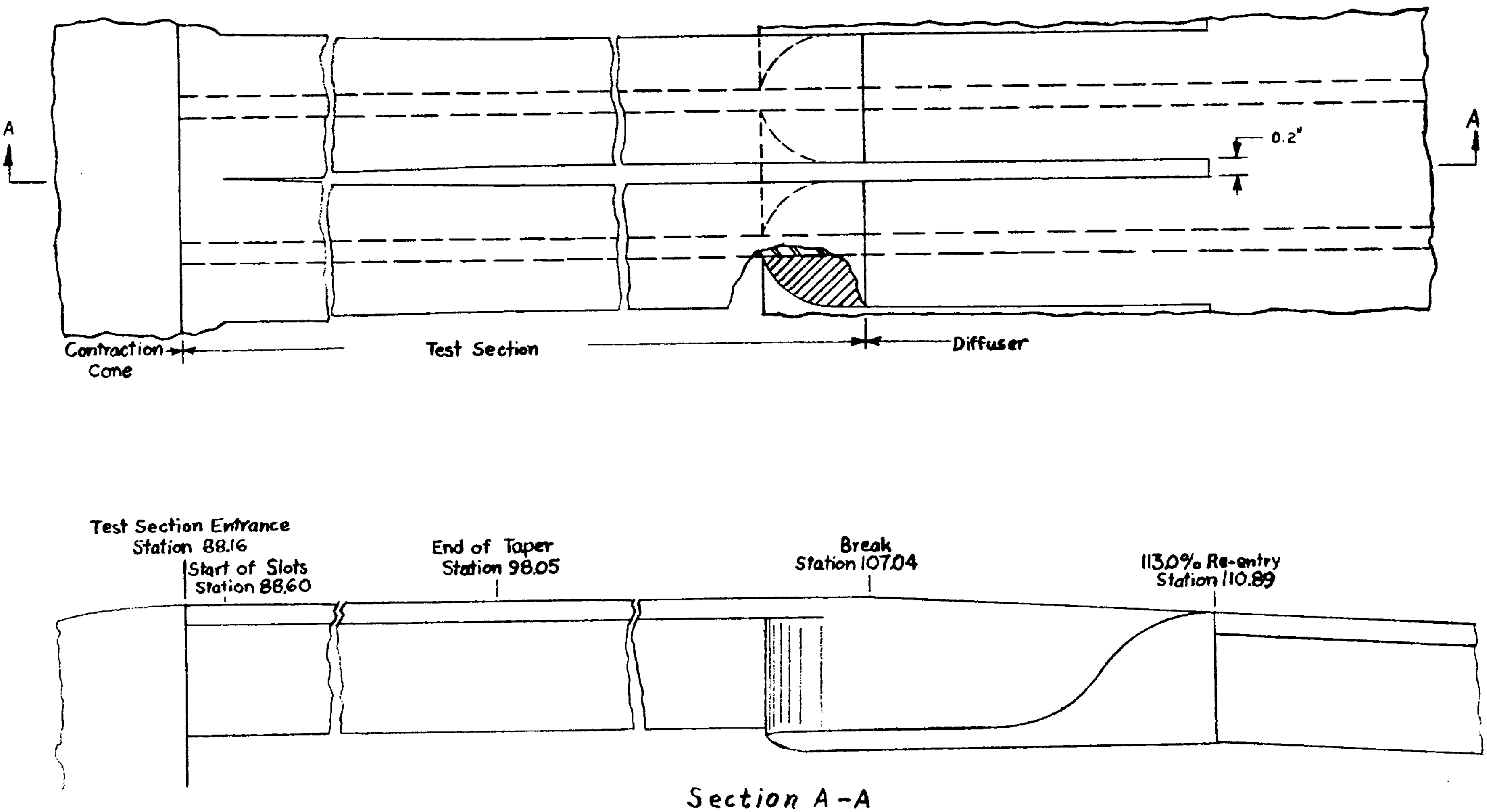


Figure 4 -Sketch Showing Details of Slotted Wall

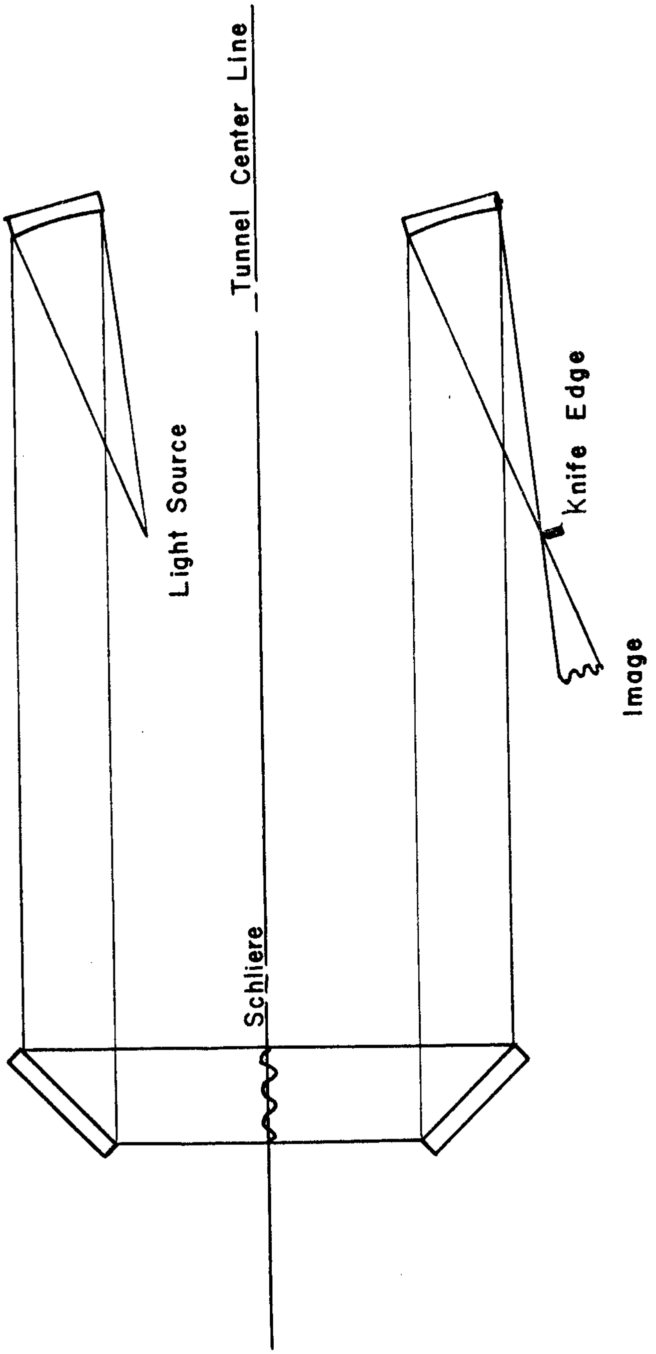
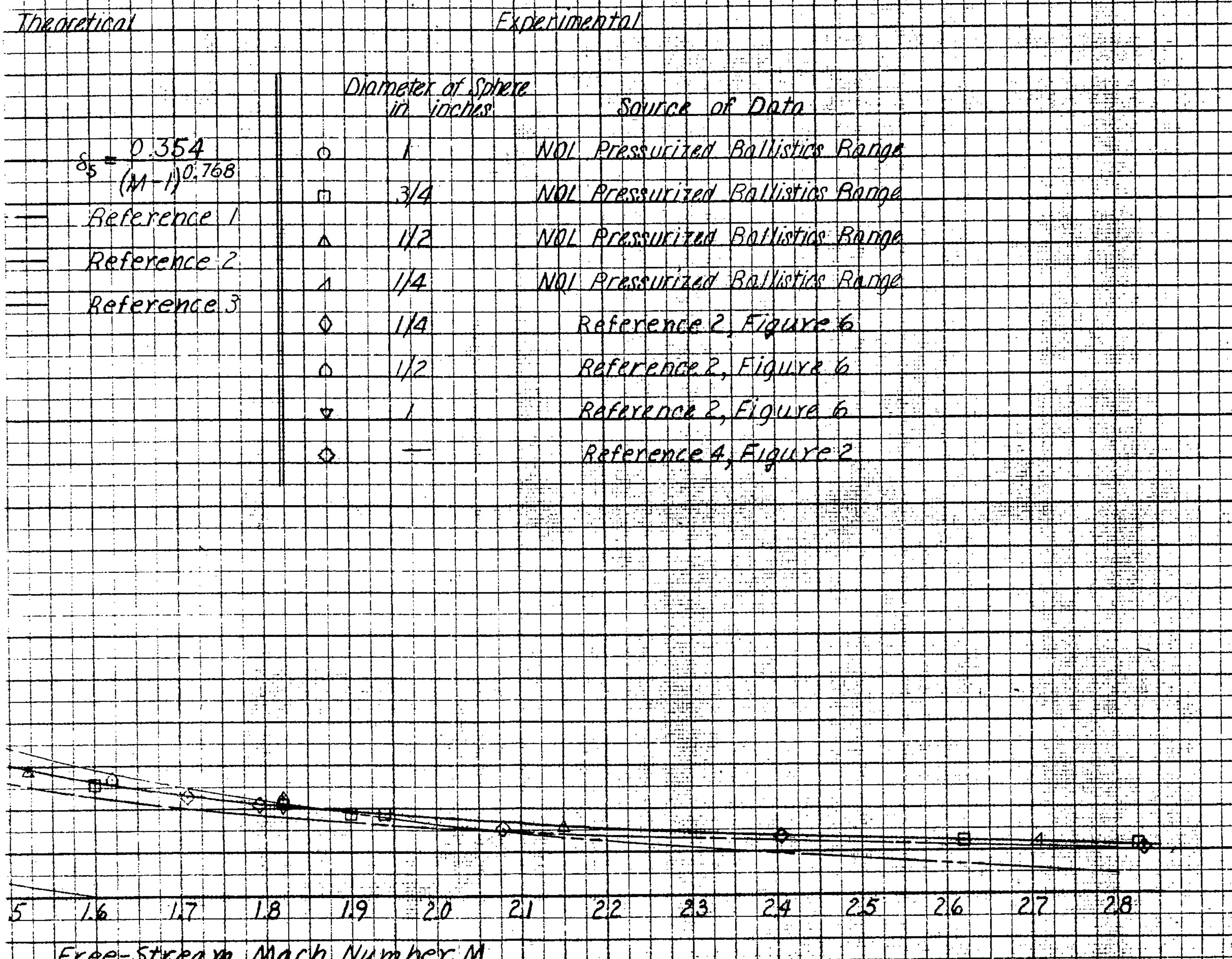


Figure 5-Diagram of 1/12-Scale Model Tunnel Schlieren System



...mparison of Extrapolated Empirical Equation Having Horizontal Asymptote Equal to Zero With Various Experimental Results

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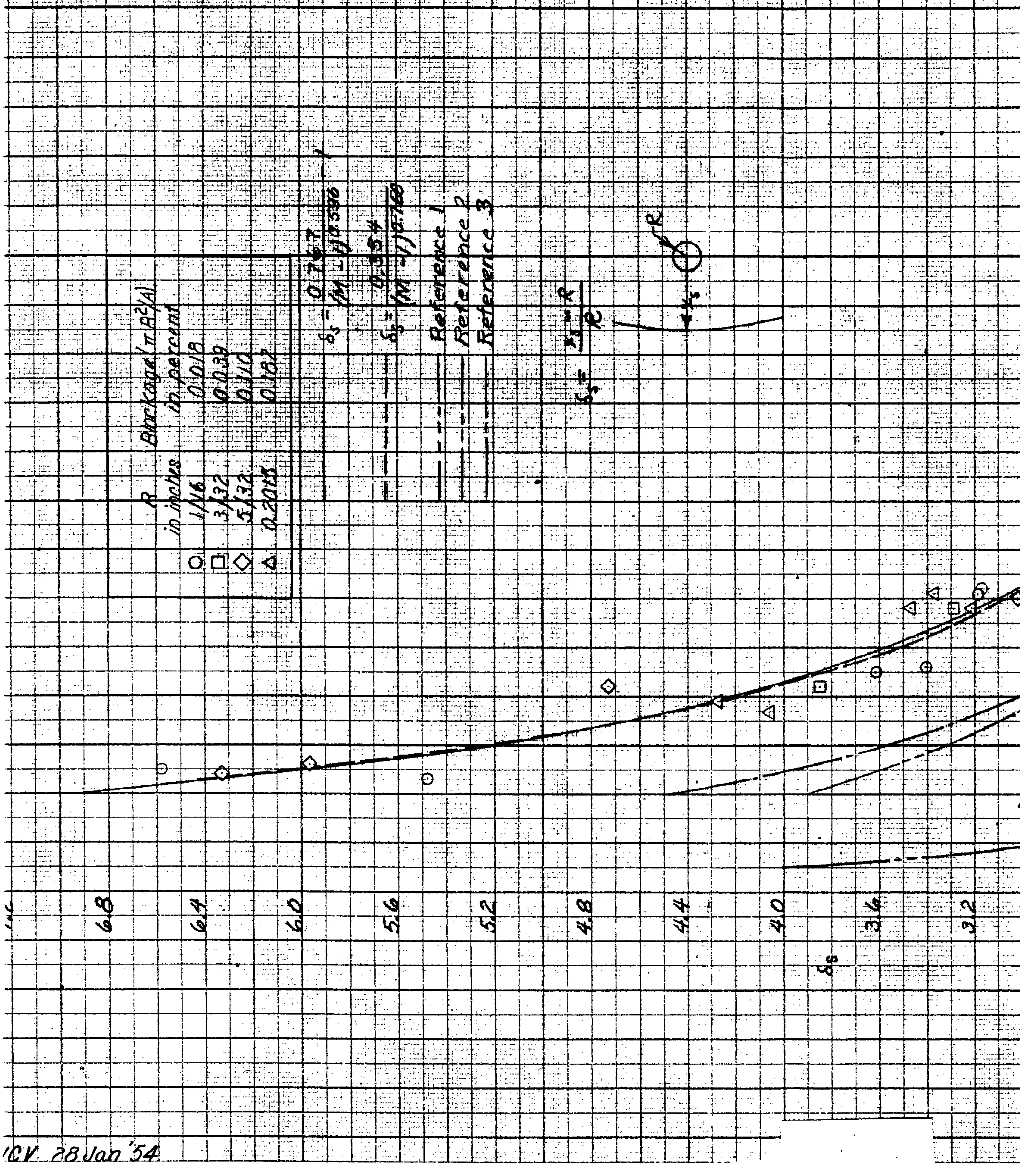
FIGURE 7


R
in inches
1/16
3/32
5/32
0.2015
Blockage (πR²/A)
in percent
0.018
0.039
0.110
0.182
δs = 0.767/(M-1)^0.536
δs = 0.354/(M-1)^0.768
Reference 1
Reference 2
Reference 3
δs = ξs/R
R
ξs
6.8
6.4
6.0
5.6
5.2
4.8
4.4
4.0
3.6
3.2
δs

CV 28 Jan '54

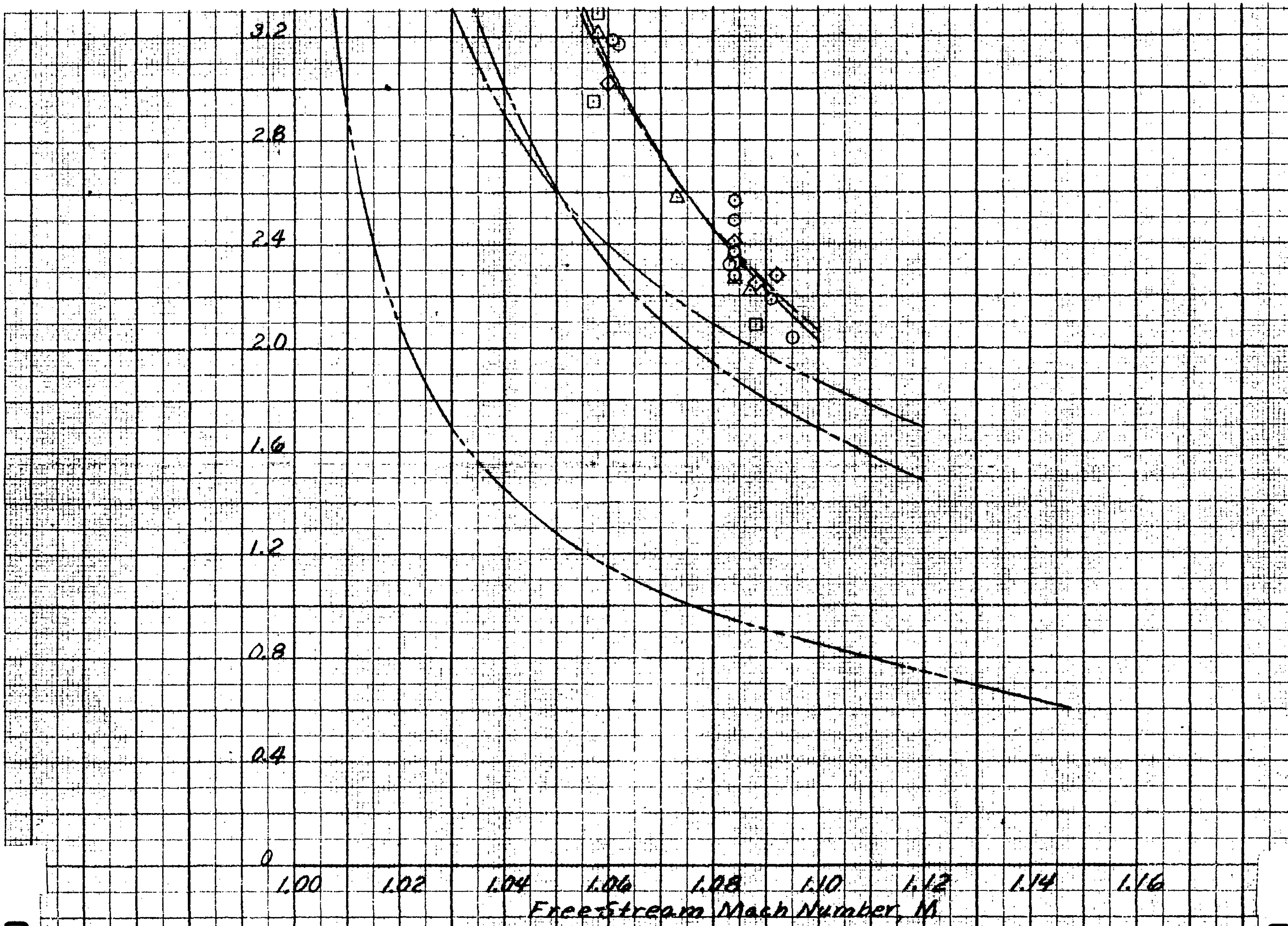


Figure 6 - Comparison of Experimental Values of Bow-Wave-Detachment Distance With Theoretical and Empirical Curves

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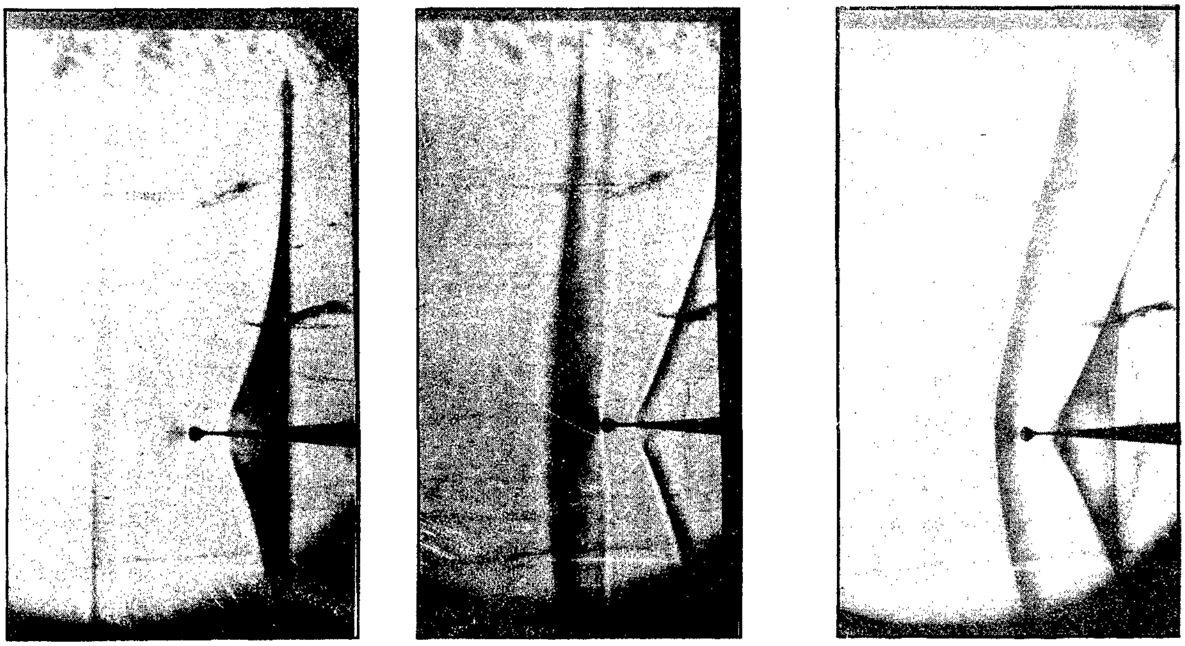
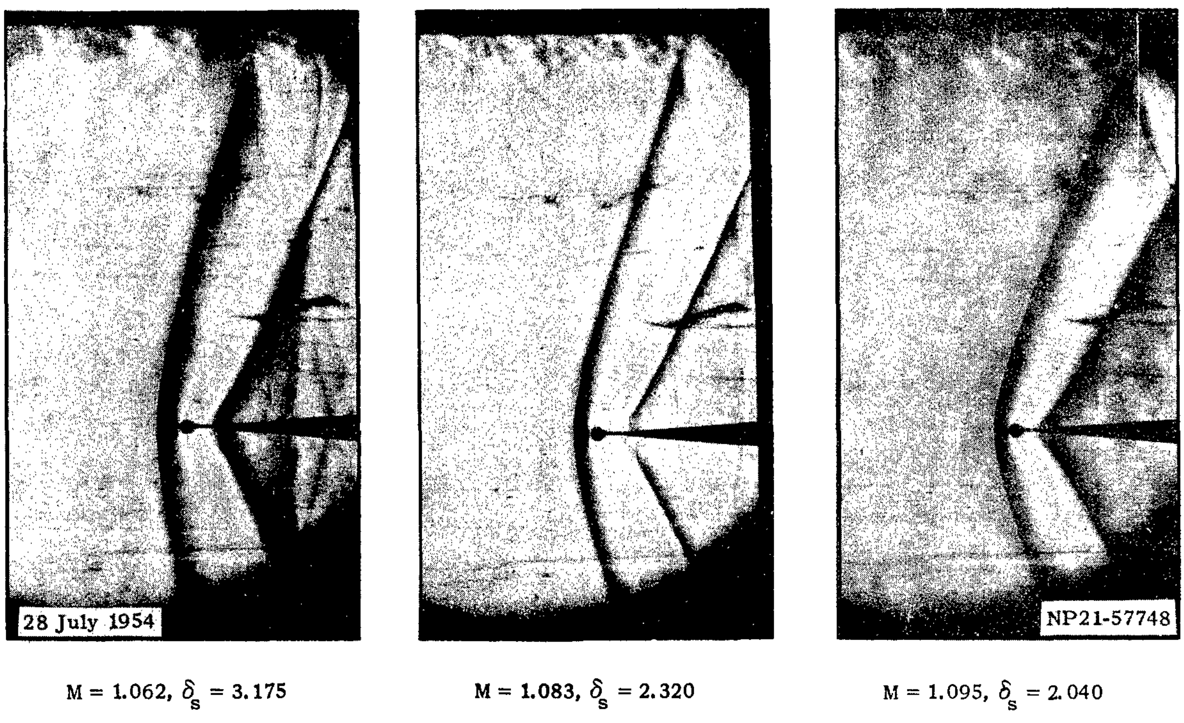


M = 1.004 | M = 1.025, δ_s = 6.579 | M = 1.046, δ_s = 3.404



M = 1.062, δ_s = 3.175 | M = 1.083, δ_s = 2.320 | M = 1.095, δ_s = 2.040

Figure 8 - Photographs of Horizontal Density Gradient With 1/8-Inch-Diameter Sphere Showing Bow Wave

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